

## Field occurrence of cordierite gneiss and related ultrahigh-temperature granulites from the Achankovil Shear Zone, southern India

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### Abstract

Field occurrence of cordierite gneiss and related high-grade metamorphic rocks and granites including charnockite, quartzo-feldspathic gneiss, and alkali-feldspar granite from the Achankovil Shear Zone, southern India, is discussed to infer the origin of this unique lithology. Cordierite gneiss often occurs between the lithological boundary between layers of quartzo-feldspathic gneiss and host charnockite or as thin lenses or layers within charnockite adjacent to the quartzo-feldspathic gneiss. The textures suggest reactions between felsic (migmatitic) melt and charnockite as a possible mechanism to form cordierite gneiss. The formation of cordierite gneiss probably took place during ultrahigh-temperature ( $T \sim 980^\circ\text{C}$  at 8-10 kbar) peak metamorphism of the zone related to the amalgamation of the Gondwana supercontinent during Neoproterozoic to Cambrian.

**Keywords:** cordierite gneiss, ultrahigh-temperature granulite, Achankovil Shear Zone, southern India

### Introduction

The Achankovil Shear Zone (ACSZ) in southern India has been traced out as a major lineament of 8-10 km in width and >100 km length (Fig. 1; Drury and Holt, 1980; Drury et al., 1984) with a pronounced magnetic anomaly (Rajaram et al., 2003). This zone separates two major Neoproterozoic to Cambrian crustal blocks in southern India, namely the Trivandrum Block to the south and the Madurai Block to the north. The Trivandrum Block is composed dominantly of layered sequence of khondalite (garnet-sillimanite-biotite-graphite gneiss) and leptynite (leucocratic garnet gneiss). Incipient charnockite is also a dominant lithology in the block. The Madurai Block, one of the largest crustal blocks in southern India, is composed mainly of biotite-hornblende orthogneiss and massive charnockite with supracrustal rocks such as pelitic and mafic granulites, quartzite, calc-silicate rocks, and Mg-Al-rich rocks. Recent petrological data

from the Trivandrum and Madurai Blocks indicate crustal metamorphism at extreme thermal conditions of  $T \sim 1000^\circ\text{C}$  and  $P \sim 10$  kbar (e.g. Brown and Raith, 1996; Tateishi *et al.* 2004; Morimoto et al., 2004; Sajeev et al., 2004; Tsunogae and Santosh, 2006, 2009). The boundary between the ACSZ and the Trivandrum block is sharply defined by the Tenmalai shear zone, whereas that with the Madurai Block is apparently gradual.

The rocks in the ACSZ display a prominent NW-SE trending foliation with steep dips to southwest formed by initial dextral deformation and later sinistral transpressional deformation (Rajesh and Chetty, 2006). Geochronological investigation of the high-Al orthopyroxene-bearing granulites suggests that the peak metamorphism took place at 580-600 Ma (Santosh et al., 2009b). The major lithology of the zone comprises charnockite, khondalite, leptynite, hornblende gneiss, garnet-cordierite gneiss, mafic granulite, quartzite (possibly metachert; Santosh et al., 2009a), and calc-silicate rocks, which are intruded by Cambrian alkali-feldspar granites (e.g., Santosh, 1987; Rajesh et al., 2004; Santosh et al., 2005). Among the various lithologies present in the ACSZ, cordierite-bearing gneiss is a unique lithology which is present only in the ACSZ and the southernmost part of the Madurai Block. Although numerous petrological and geothermobarometric studies of the ACSZ has been done on the cordierite-bearing gneisses (e.g., Santosh, 1987; Nandakumar and Harley, 2000; Cenko et al., 2002; Ishii et al., 2006; Shimizu et al., 2009) and they yielded very high- $P$ - $T$  conditions of  $920$ - $980^\circ\text{C}$  and 8-10 kbar as a time of the peak metamorphism (e.g., Shimizu et al., 2009), no detailed descriptions of the field occurrence of cordierite gneiss and its relationship with adjacent lithologies has been reported so far. In this study, we assembled available field geological data from six representative localities within the ACSZ area and compared the occurrence of cordierite gneiss from different localities. Our study has implications in understanding the petrogenesis of cordierite gneiss and related ultrahigh-temperature metamorphic rocks in the ACSZ region which probably corresponds to a suture zone formed in a collisional setting associated with the final assembly of the

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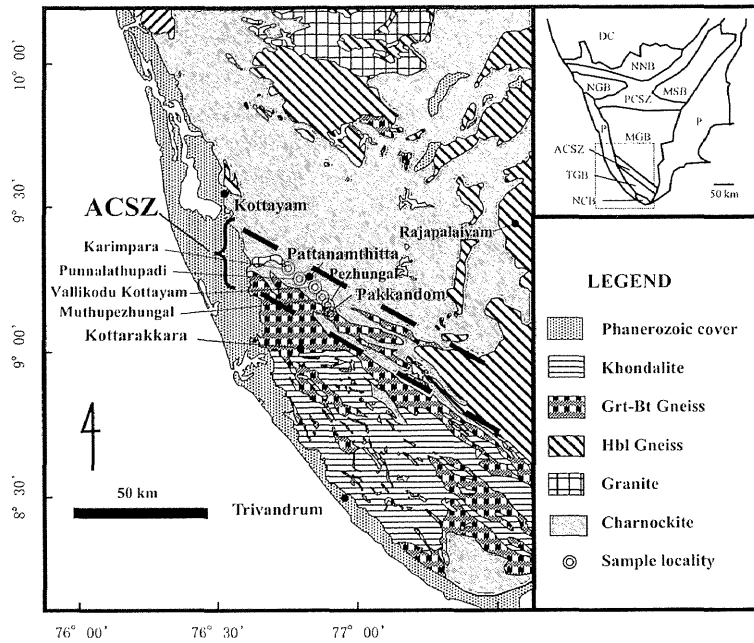


Fig. 1. Simplified geological map of the southern part of Kerala and Tamil Nadu (after GSI, 1995a, b) with the sample localities of cordierite gneiss discussed in this paper. DC: Dharwar Craton, MGB: Madurai Block, MSB: Madras Block, NNB: Northern Block, NGB: Nilgiri Block, TGB: Trivandrum Block, NCB: Nagarcoil Block, ACSZ: Achankovil Shear Zone, PCSZ: Palghat-Cauvery Shear Zone, P: Phanerozoic cover.

Gondwana supercontinent (Santosh et al., 2009a; Shimizu et al., 2009).

### Field occurrence

Samples of cordierite gneiss and associated ultrahigh-temperature granulites discussed in this study were collected from six localities within the ACSZ (see Fig. 1) during the field trip to southern India in 2003, 2004, and 2008: Punnalathupadi (locality KR2-1), Vallikodu Kottayam (locality KR6-5), Muthupezhungal (locality KR11-1), Karimpara (locality KR11-3), Pezhungal (locality KR18-1), and Pakkandom (locality KR19-5). Cordierite gneiss is characterized by bluish patches or laths of cordierite aggregates in hand specimen. Below we will describe field occurrence of cordierite-bearing gneiss and associated granulites and discuss their relationships and petrogenesis.

Punnalathupadi (KR2-1), located about 4 km west-southwest from Pattanamthitta (cf. Santosh, 1987), is an open active quarry consists dominantly of cordierite gneiss, charnockite, and quartzo-feldspathic gneiss, with minor mafic granulite. All the lithologies show gneissose structure with obvious NNW-SSE to NW-SE trending strong foliation, which is consistent with the regional foliation trend of the ACSZ (e.g., Rajesh and Chetty, 2006). Orthopyroxene-bearing mafic granulite layer of about 70 cm to 1 m in thickness,

probably metavolcanic in origin, is also present parallel to the foliation (Fig. 2a). Cordierite-bearing gneiss (or cordierite gneiss) in this locality often occurs along the lithological boundary between leucocratic (quartzo-feldspathic) gneiss and charnockite. As shown in Fig. 2b, cordierite-rich layers of about 2 to 10 mm in thickness in charnockitic matrix are present parallel to the foliation of adjacent quartzo-feldspathic gneiss.

Vallikodu Kottayam (KR6-5) is located about 3 km south-southeast from Pattanamthitta town as an extension of KR2-1 locality. It is a large active quarry composed mainly of cordierite gneiss, charnockite, and quartzo-feldspathic gneiss (Fig. 2c). The rocks also display a NNW-SSE foliation similar to the previous locality. Alkali-feldspar granite occurs as sheets of about 1 to 3 m in thickness nearly parallel to, or slightly oblique to the matrix gneissic foliation (Fig. 2d). It is pinkish in color probably due to the alteration of alkali-feldspars. Similar association of granulites and post-tectonic alkali granites is a common feature of the ACSZ as reported in previous studies (e.g., Santosh, 1987; Rajesh et al., 1996; Santosh et al., 2005). However, the granite is in part folded together with the matrix granulites (Fig. 2e), suggesting that the intrusion of alkali-feldspar granite is not post-tectonic in this locality, but predates intense deformation possibly during high-grade metamorphism. Quartzo-feldspathic gneiss is coarse-

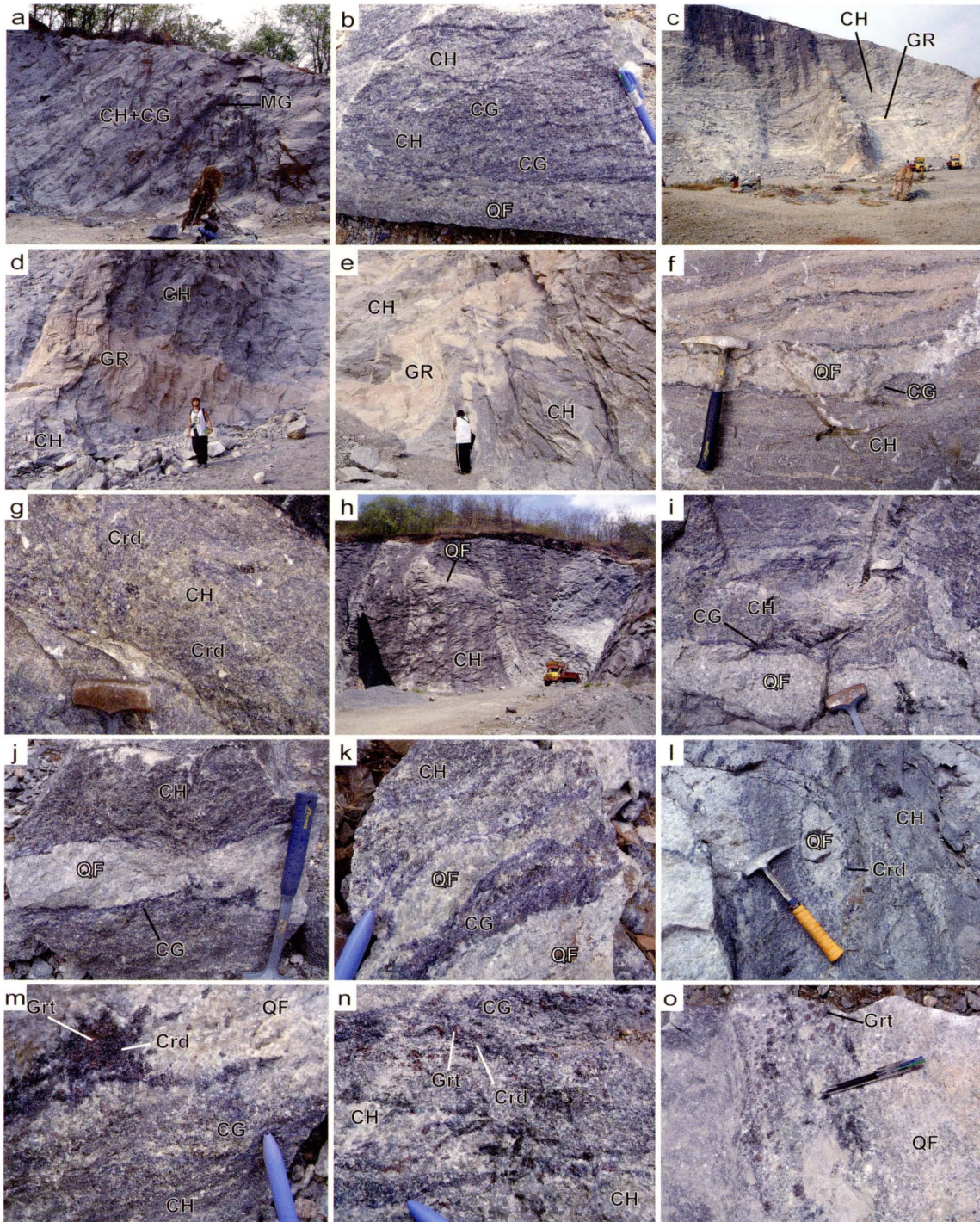


Fig. 2. Field occurrence of high-grade metamorphic rocks in Punnalathupadi (a, b), Vallikodu Kottayam (c to g), and Muthupezhungal (h to o) within the Achankovil Shear Zone. GR: alkali-feldspar granite, QF: quartzo-feldspathic gneiss, CG: cordierite gneiss, MG: mafic granulite Grt: garnet, Crd: cordierite, CH: charnockite, Amp: calcic amphibole. (a) a layer of MG in layered gneiss (CH + CG), (b) Crd-rich layers (CG) in CH aligned parallel to the foliation of adjacent QF. (c) Vallikodu Kottayam quarry composed mainly of CH and GR. (d). A sheet of GR nearly parallel to the matrix gneissic foliation. (e) GR is folded together with the matrix CH. (f) CG present between QF and CH. (g) Crd patches in CH matrix. (h) Occurrence of gneisses in Muthupezhungal locality. (i) CG present between folded QF and CH. (j) Thin layer of CG present between QF and CH. (k) A remnant of CG is present as an enclave in QF. (l) Crd aggregates around a boudin of QF elongated along the foliation of CH. (m) Crd mantling Grt in QF. (n) Grt-Crd association in CG within CH. (o) Grt in QF without retrograde Crd rim.

grained and occurs as layers nearly parallel to the weak foliation of charnockite (Fig. 2f). Cordierite-rich layers are often present along the boundary between the quartzo-feldspathic gneiss and charnockite (Fig. 2f). Cordierite is also present as patches in orthopyroxene-bearing (charnockitic) matrix (Fig. 2g). Such rock type has been described as garnet-orthopyroxene-cordierite granulite or orthopyroxene-bearing cordierite gneiss in previous studies (e.g., Ishii et al., 2006).

Muthupezhungal locality (KR11-1) is a large active quarry composed mainly of cordierite gneiss, charnockite, and quartzo-feldspathic gneiss (Fig. 2h). The rocks also display a NNW-SSE foliation similar to the other localities. In this locality, the relationship of cordierite gneiss with charnockite and quartzo-feldspathic gneiss can be clearly seen (e.g., Figs. 2i, j). As the figures demonstrate, cordierite gneiss occurs along the boundary between quartzo-feldspathic gneiss and charnockite. A remnant of cordierite-garnet-biotite gneiss is also present as an enclave in the quartzo-feldspathic gneiss (Fig. 2k), possibly suggesting that the quartzo-feldspathic gneiss corresponds to originally felsic melt that reacted with surrounding charnockite resulting formation of cordierite-rich gneiss between the two lithologies. Cordierite is also concentrated around a boudin of quartzo-feldspathic rock elongated along the foliation of matrix charnockitic gneiss (Fig. 2l). This texture may imply that cordierite formation also took place after the major deformation stage, probably during or after the peak metamorphism. Garnet in quartzo-feldspathic gneiss is often surrounded by cordierite (Fig. 2m), which is regarded as the formation of some cordierites by breakdown of garnet due to decompression as will be discussed in detail in the next chapter. Such a cordierite-garnet association can also be found in cordierite gneiss within charnockite adjacent to quartzo-feldspathic gneiss (Fig. 2n). In contrast, garnet in garnet- and biotite-rich layers within quartzo-feldspathic gneiss, which is apart from the contact with charnockite, is idioblastic to subidioblastic and not mantled by cordierite. The presence or absence of retrograde textures is probably controlled by different bulk-rock chemistry (Fig. 2o).

Karimpara quarry (KR11-3), located in the northernmost part of the studied area in the ACSZ, is composed mainly of cordierite gneiss, charnockite, mafic granulite, quartzo-feldspathic gneiss, and alkali-feldspar granite. Foliation of these rocks is relatively weak (Fig. 3a) compared to other outcrops. Garnet in quartzo-feldspathic gneiss is mantled by cordierite (Fig. 3b). A similar reaction texture from garnet to cordierite is also shown in Fig. 2m.

Pezhungal locality (KR18-1), about 14 km north-northeast from Kottarakkara, is a large active quarry that comprises cordierite gneiss, charnockite, quartzo-feldspathic gneiss, and alkali-feldspar granite. The rocks also display a NNW-SSE foliation that is concordant with the other localities. Granulites in this outcrop are in part isoclinally folded as traced by folded quartzo-feldspathic gneiss layers up to 1 m in thickness (Fig. 3c). Cordierite gneiss in this locality is quartzo-feldspathic and occurs between granoblastic quartzo-feldspathic gneiss and charnockite, which is similar to the texture in Muthupezhungal (Fig. 2i). The boundary between the cordierite gneiss and surrounding rock is gradual, probably because of assimilation between quartzo-feldspathic (migmatitic) felsic melt and charnockite at high-temperature (Fig. 3d). Thin bluish lenses or layers of cordierite gneiss are also present in garnet-bearing charnockite (Fig. 3e). In the cordierite-garnet association, garnet is always mantled by cordierite, suggesting the formation of garnet after cordierite (Fig. 3f).

Pakkandom (KR19-5), about 12 km NNE from Kottarakkara, is an extensive open quarry that exposes garnet-cordierite gneiss, charnockite, quartzo-feldspathic gneiss, and alkali-feldspar granite. The rocks show NNW-SSE to NW-SE foliation dipping steeply to southwest. This locality is characterized by the occurrence of huge pinkish alkali-feldspar granite body of about 50 m in thickness (Fig. 3g). The granite intrudes parallel to, or slightly oblique to the gneissic foliation (Fig. 3h). It contains dark greenish patches composed of aggregates of calcic amphibole (Fig. 3i). Cordierite gneiss in this locality is present between quartzo-feldspathic gneiss and charnockite, which is similar to the occurrence of other localities (e.g., Figs. 2f, i). However, cordierite gneiss in Pakkandom is strongly foliated as defined by aligned biotite and cordierite aggregate (Fig. 3j, k). In contrast, quartzo-feldspathic gneiss here is less foliated and contains abundant subidioblastic garnet and biotite (Fig. 3l).

### Petrography

More than 200 thin sections of cordierite gneiss and related granulites were examined to describe mineral assemblages and reaction textures. The most common assemblage of the rock type is defined by cordierite, garnet, orthopyroxene, quartz, plagioclase, spinel, ilmenite, and magnetite with accessory biotite, sillimanite and K-feldspar. There is no significant difference in mineral assemblage of the rocks from the six localities. Sillimanite, if present, occurs only as rare inclusions in subidioblastic garnet. In sample KR2-1E,

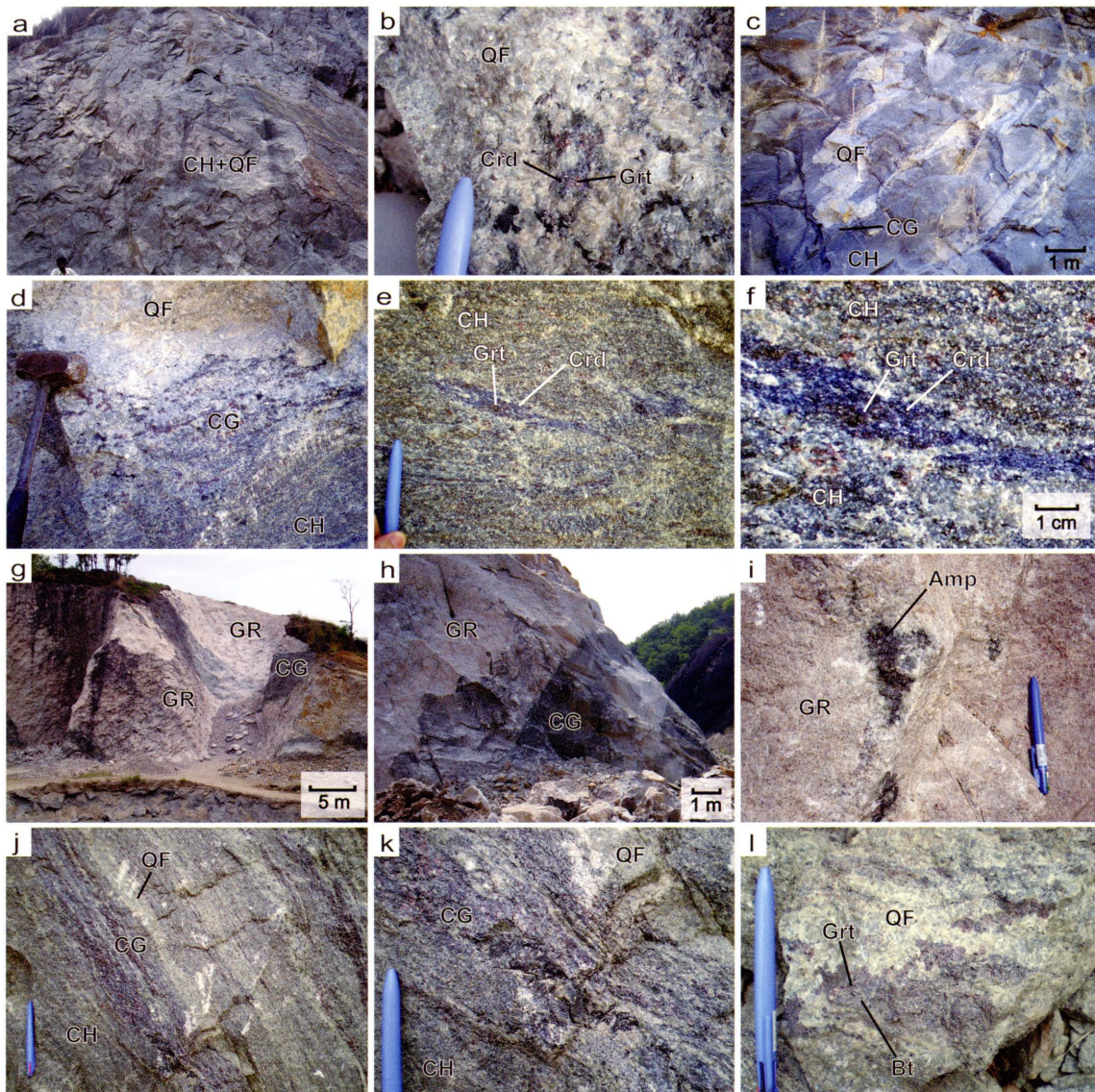
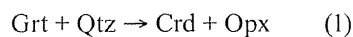
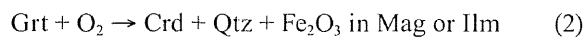


Fig. 3. Field occurrence of high-grade metamorphic rocks in Karimpara (a, b), Pezhungal (c to f), and Pakkandom (g to l) within the Achankovil Shear Zone. See Fig. 2 for abbreviations. (a) Occurrence of gneisses in Karimpara locality. (b) Crd mantling Grt in QF. (c) Isoclinally folded QF from Pezhungal. (d) CG present between QF and CH. (e) Thin layers of CG in garnet-bearing CH. (f) Crd mantling Grt in CH. (g) Huge pinkish alkali-feldspar granite body in Pakkandom. (h) GG present parallel to the foliation of adjacent CH. (i) Dark greenish patches of calcic amphibole in GR. (j) and (k) Strongly foliated CG present between QF and CH. (l) Grt and Bt in weakly foliated QF.

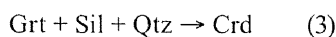
a representative sample from Punnalathupadi, strongly pleochroic and subidioblastic orthopyroxene occurs commonly with cordierite, perthite, and quartz (Fig. 4-1a, b). Such orthopyroxene is extremely rich in  $\text{Al}_2\text{O}_3$  (up to 7.3 wt.%) as an evidence of extremely high-temperature metamorphism (Hensen and Harley, 1990; Harley, 2004). Cordierite in sample KR2-1D forms poikiloblastic aggregates of subhedral grains and contains numerous inclusions of zircon, monazite, and quartz. Some cordierites around garnet are intergrown with irregular-shaped orthopyroxene as orthopyroxene-cordierite symplectite probably formed by the following reaction:



The reaction texture has been reported by Nandakumar and Harley (2000) and Ishii et al. (2006) from the ACSZ as an evidence of retrograde metamorphism, as well as other granulite terranes worldwide (Harley, 1989). Symplectitic fine-grained aggregate of cordierite and quartz occurs around subhedral to anhedral garnet. In places, aggregates of cordierite and quartz are closely associated with magnetite and ilmenite (Fig. 4-1c, d). Such a texture suggests the reaction,



Similar textures are present in samples KR19-5B (Figs. 3e, f) from Pakkandom and KR18-1L (Fig. 4-2g, h) from Pezhungal. Cordierite and quartz aggregates around garnet are also closely associated with magnetite and ilmenite in sample KR19-5B and KR18-1L. In sample KR19-5G1 from Pakkandom, cordierite is present as a matrix phase coexisting with quartz- and sillimanite-bearing garnet (Fig. 4-2i, j). It often mantles garnet, suggesting the progress of following reaction:



This sample contains the direct contact of fine-grained spinel and quartz (Fig. 4-2k, l). Such spinel + quartz association has been regarded as one of the indicators for decompression at ultrahigh-temperature conditions.

## Discussion

Detailed field observations of cordierite gneiss and related high-grade metamorphic rocks and granites including charnockite, quartzo-feldspathic gneiss, and alkali-feldspar granite indicate that cordierite gneiss commonly occurs between the lithological boundary between charnockite and quartzo-feldspathic gneiss

(e.g., Fig. 2j). The boundary between the cordierite gneiss and surrounding rocks is often gradual (Fig. 3d), and cordierite gneiss is rarely enclosed apparently as “enclaves” in quartzo-feldspathic gneiss (Fig. 2k). The textures suggest that the quartzo-feldspathic gneiss is likely to be a product of partial melting during prograde metamorphism. The intrusion of the felsic melt to produce quartzo-feldspathic rock into charnockite, and subsequent reaction between the migmatitic melt and host charnockite is a possible mechanism to form cordierite gneiss.

Such reactions between melt and charnockite that resulted in the formation of cordierite are probably related to ultrahigh-temperature metamorphism of the ACSZ. Recent  $P$ - $T$  estimates of cordierite gneiss and associated lithologies by Ishii et al. (2006) demonstrated ultrahigh-temperature peak metamorphic conditions of  $T = 940$ - $1040^\circ\text{C}$  at 8.5-9.5 kbar on garnet-orthopyroxene-plagioclase-quartz assemblage, Al-solubility in orthopyroxene, and ternary feldspar in cordierite gneiss of Punnalathupadi and Vallikodu Kottayam within the ACSZ. This  $P$ - $T$  condition is considerably higher than the previously reported values. The retrograde conditions were obtained from cordierite-bearing geothermobarometers at 3.5-4.5 kbar and  $720 \pm 60^\circ\text{C}$ . Shimizu et al. (2009) recently reported equilibrium spinel + quartz assemblage enclosed within garnet in garnet-orthopyroxene-cordierite granulites from Pakkandom for the first time from the ACSZ. The spinel that directly contacts with quartz is poor in Zn and  $\text{Fe}^{3+}$  ( $X_{\text{Zn}} = \text{Zn}/(\text{Fe}_2^+ + \text{Mg} + \text{Zn}) = 0.027$ - $0.036$ ,  $\text{Fe}^{3+}/(\text{Fe}^{2+} + \text{Fe}^{3+}) = 0.12$ - $0.17$ ). Such Zn- and  $\text{Fe}^{3+}$ -poor spinel has been regarded as a diagnostic evidence of ultrahigh-temperature metamorphism (e.g., Harley, 1998). The high-temperature stability of the spinel + quartz is also supported by the results of geothermobarometric calculation of garnet-orthopyroxene assemblages that provides robust evidence for peak ultrahigh-temperature metamorphism at  $920$ - $980^\circ\text{C}$  and 8-10 kbar (Fig. 5), which was further confirmed by Al-solubility in orthopyroxene and magnetite-ilmenite geothermometers ( $900$ - $950^\circ\text{C}$  and  $\sim 1000^\circ\text{C}$ , respectively) (Shimizu et al., 2009). The peak ultrahigh-temperature event was followed by decompression event down to 4.0-4.2 kbar and  $640$ - $670^\circ\text{C}$ , toward the stability of cordierite along a clockwise  $P$ - $T$  path (Fig. 5).

The recent tectonic model on the southern granulite terrane in India regards the ACSZ as a possible major suture zone related to the southward subduction and accretion of the Trivandrum and Madurai Blocks (Santosh et al., 2009a). The ultrahigh-temperature metamorphism and the formation of unique cordierite-

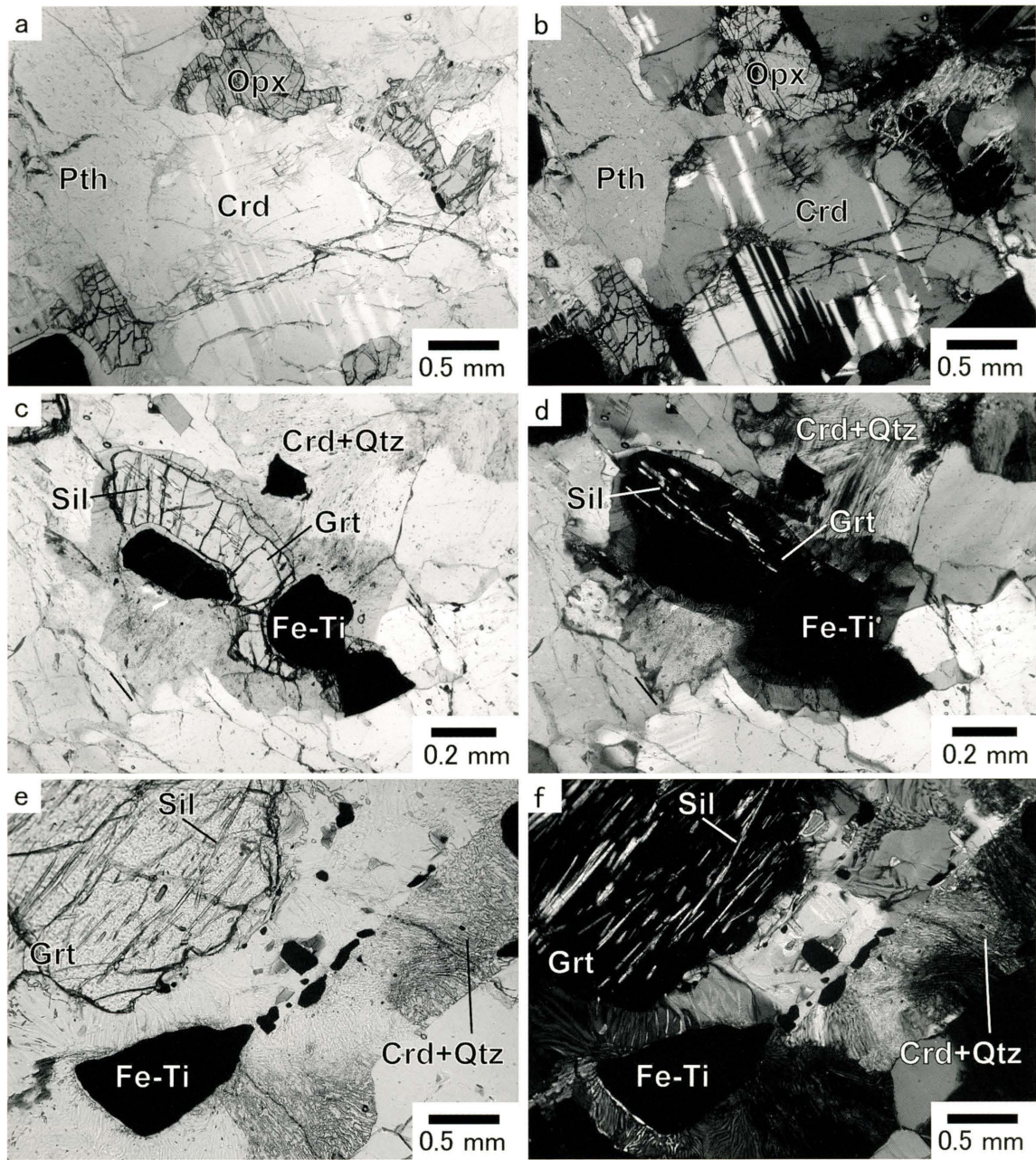


Fig. 4-1. Photomicrographs of representative cordierite gneisses discussed in this study. (a), (c), (e), (g), (i) and (k) are taken by polarized light, whereas (b), (d), (f), (h), (j) and (l) are crossed-polar photographs. (a), (b) Strongly pleochroic subidioblastic orthopyroxene coexisting with cordierite and perthite (sample KR2-1E). (c), (d) Symplectitic fine-grained aggregates of cordierite and quartz around subidioblastic to xenoblastic garnet and Fe-Ti oxide (magnetite and ilmenite) (sample KR2-1D). (e), (f) Cordierite + quartz aggregate around garnet and Fe-Ti oxide (magnetite and ilmenite) (sample KR19-5B). Silimanite, present only as inclusions in garnet, is aligned along the matrix foliation.

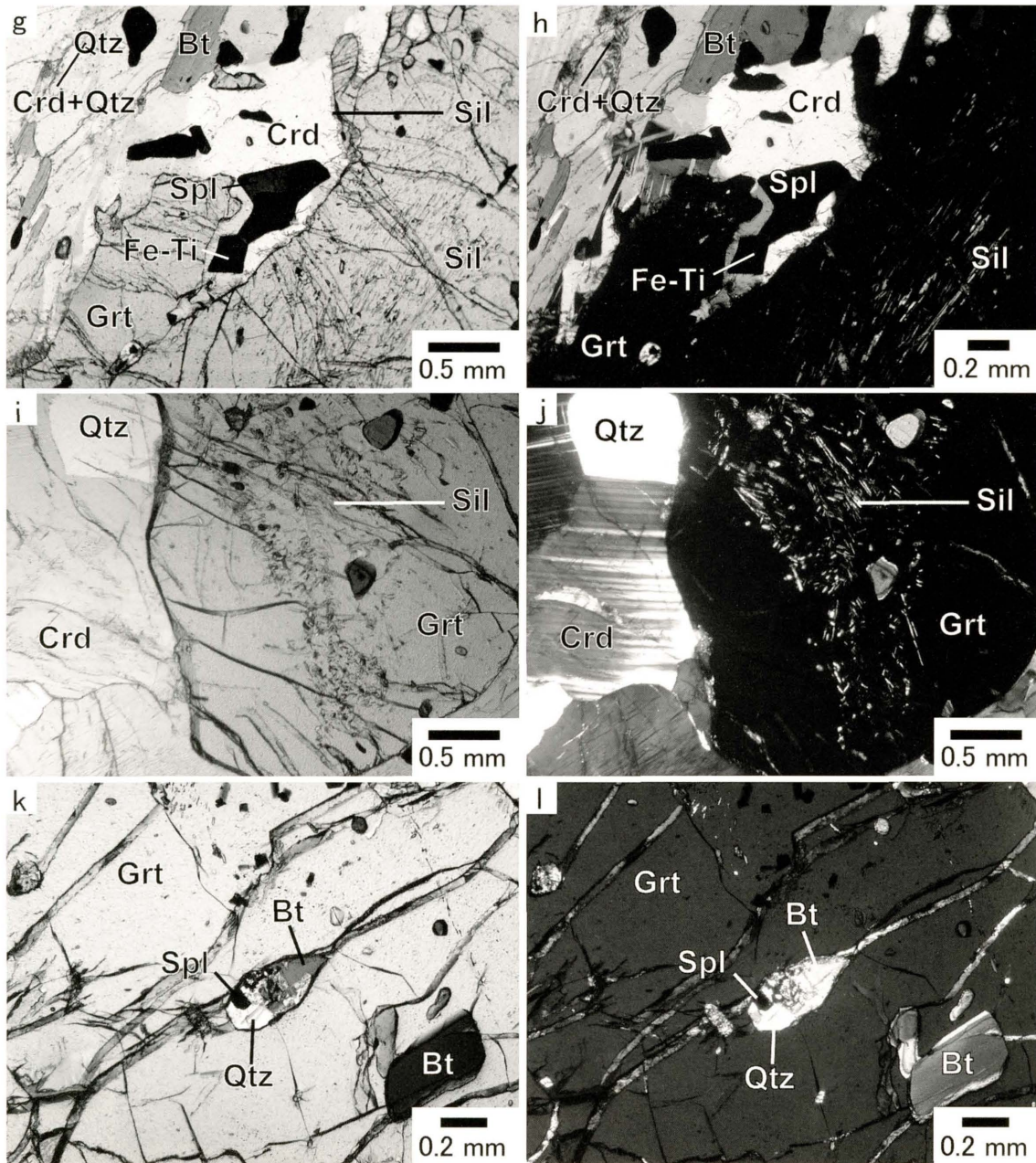


Fig. 4-2. (g), (h) Cordierite + quartz symplectite and magnetite + ilmenite + spinel aggregate around subidioblastic to xenoblastic garnet (sample KR18-1L). (i), (j) Coarse-grained subidioblastic cordierite coexisting with quartz and sillimanite-bearing garnet (sample KR19-5G1). (k), (l) The coexistence of spinel and quartz in garnet as an indicative of ultrahigh-temperature metamorphism (sample KR19-5G1).



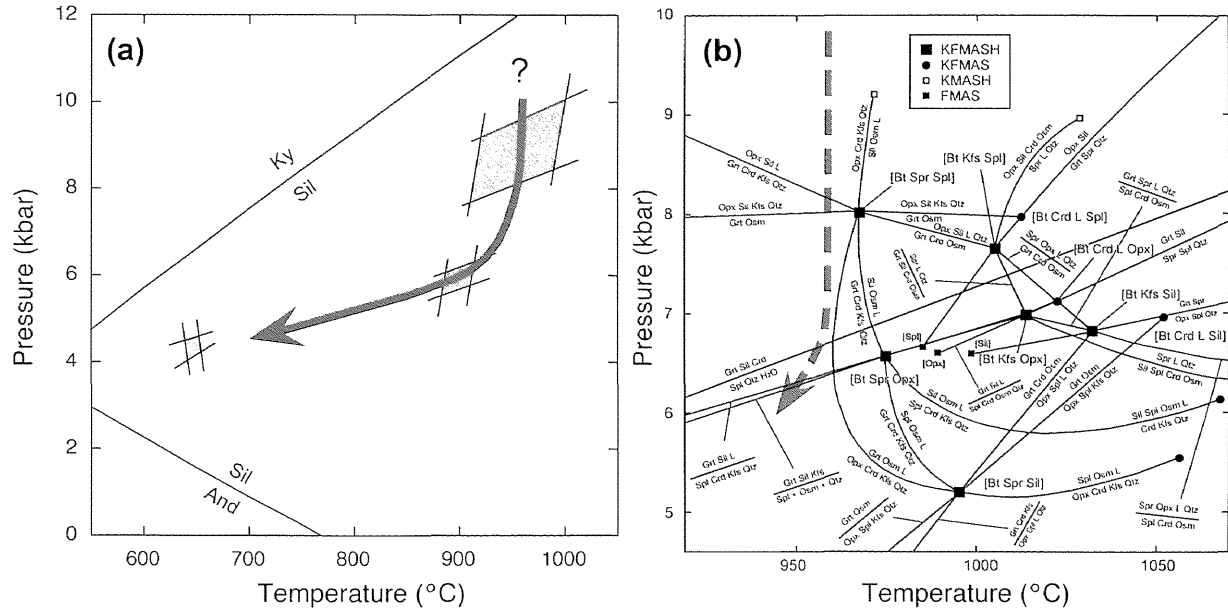


Fig. 5.  $P$ - $T$  diagrams showing pressure-temperature path (arrays) for cordierite gneisses from Pakkandom in the ACSZ after Shimizu et al. (2009). (a)  $P$ - $T$  path based on geothermobarometric observations. (b)  $P$ - $T$  path based on phase analysis of KFMASH petrogenetic grid after Kelsey et al. (2004). See Shimizu et al. (2009) for further discussion.

bearing gneisses in the ACSZ discussed in this study provides an evidence for the formation and exhumation of extreme metamorphic rocks along this zone during the final collisional assembly along the trace of this Gondwana suture.

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